# Rover attitude determination using kinematics model and its applications in Pragyan operations

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***Abstract*—Rover plays an important role in planetary exploration missions. They serve as mobile laboratory traversing over challenging terrains to carry out in situ scientific experiments. One crucial part of path planning is to ensure safety of rover as it traverses uneven terrain covered with boulders & craters. This paper deals with kinematic modelling of a 6-wheel rocker-bogie rover and its application in different phases like design & mission operations. A geometric model of the rover inverse kinematics is developed to compute rover attitude as a function of terrain. This model is used to select a path which has less chances of the rover toppling. The model accuracy is proved by carrying out experiments on calibrated test bed. The application of this model during Pragyan mobility operations, post Chandrayaan-3 landing on 23 Aug, 2024 is illustrated.**

***Keywords—kinematic model, rocker-bogie, inclinometer sensor modeling***

## I. INTRODUCTION

The first section deals with mathematical modelling of the inclinometer sensor. The inclinometer is mounted on the rover chassis and senses the rover tilt angles. It is used as safety device which cuts of mobility if the tilt angles exceeds predefined limits. The sensor model is based on the inverse kinematic model of a 6-wheel rocker -bogie system [1]-[4]. To assess the accuracy of the model, the output is compared with the actual sensor reading. For this, the rover was placed on a calibrated test bed with obstacles of known heights and sensor readings was compared with the model output.

Section III highlights the applications of this mathematical model in computing crater depth. Since the model computes the rover attitude as a function of all 6 wheel contact terrain height, in the absence of accurate information of crater depth in which one wheel is placed, the rover attitude data along with remaining 5 wheels contact terrain height information can be used to compute the depth of the crater.

In section IV, the model is used to determine maximum height of obstacle which can be safely scaled. This is illustrated with an example. This is used during design phase to arrive at a suitable rover dimension.

The application of the sensor model for on orbit Pragyan path planning has been covered in [5]. Path planning involves generating a safe path for the rover, which ensure that rover doesnot topple due to roll & pitch angle exceeding maximum permissible limits. The model was used to predict the roll and pitch angle as the rover traversed on uneven lunar surface. A close match was observed between the predicted angles and onboard roll, pitch data as measured by the inclinometer. This validates the model with on orbit data.

This model is relevant right from design inception phase (as illustrated in section IV) to post flight analysis.

## II. INCLINOMETER SENSOR MODEL

Inclinometer sensor measures the rover tilt angle (roll & pitch angle). The rover attitude is a function of the terrain height at the 6 wheels contact points and the rover configuration. Inclinometer sensor for Chandrayaan 3 rover, Pragyan has been developed by LEOS team. Inverse kinematic model was developed for 6-wheel rocker bogie configuration & the rover tilt angle output of the model was compared with inclinometer sensor reading for different posture of rover (obstacle placed under different wheels).

### *A. Inverse kinematic model of 6-wheel rover*

The roll, pitch angle is computed based on the inverse kinematic model. The input to the inverse kinematic model is the terrain map and rover configuration. The kinematics parameters which define the rover attitude and the rover frame is shown in Fig. 1. The configuration and the position of the rover is fully defined by ten parameters - (1) The position of the centre of the body is defined by ($x_b$, $y_b$, $z_b$) (2) The rover orientation is defined by ($\psi$ ,$\theta$, $\phi$ ) for the yaw, roll and pitch respectively and (3) The configuration of the rocker bogie mechanism is defined by the angles ($\theta_1$, $\theta_2$, $\theta_4$, $\theta_5$). The solution is derived from the basic assumption that all six wheels are in contact with terrain. Hence six closed loop equations are constructed and the set of kinematic parameters which satisfies this constraint is the rover attitude [4]. Fig 2 shows the rover wheel numbering & frame convention.

When all 6 wheels are on flat terrain both roll & pitch angle is zero i.e. $\theta = \phi = 0°$. For the given dimension of Pragyan, the angles $\theta_1 = \theta_2 = \theta_4 = \theta_5 = 26.29°$ on flat terrain.

### *B. Inclinometer data from cleanroom experiment*

The inclinometer measures the rover tilt angles roll ($\theta$) & pitch angle ($\phi$). Inclinometer ground checkout testing was carried out in cleanroom. For the 6-wheel rover, test carried out to get inclinometer sensor reading for different combinations of wheels on obstacles (obstacle of known height 105 mm). Table I gives the cases which were carried out & compares sensor reading with inverse kinematic model output. Referring to table I case 5, all left side wheels are placed on obstacles. Based on rover frame definition this results in negative roll rotation. Similarly, for case 3, when both front wheels are on obstacles, it results in negative pitch angle whereas only one wheel on obstacle (case 2) results in a combination of roll & pitch angle.

As seen in table I, a fairly good match is seen between sensor reading and model output. Given the sensor inaccuracy of 1° approximately & the safety requirement of rover roll & pitch should not exceed 20° limit this inaccuracy is tolerable.

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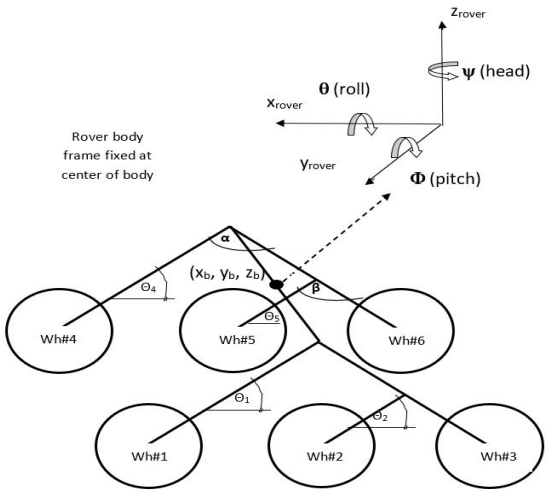


Fig. 1. Kinematic parameters

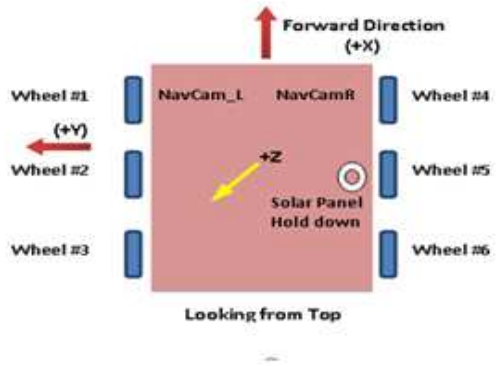


Fig. 2. Wheel numbering and rover frame convention

TABLE I. SENSOR READING & MODEL OUTPUT FOR DIFFERENT POSTURE OF ROVER

| **sl no** | | **inclinometer sensor reading for roll & pitch angle** | | **roll & pitch angle as per inverse kinematics-based sensor model (for 6-wheel rover config)** | |
|---|---|---|---|---|---|
| | ***cases*** | ***ϕ (pitch)*** | ***θ (roll)*** | ***ϕ (pitch)*** | ***θ (roll)*** |
| 1. | All wheels on floor | -0.3461 | 0.033 | 0 | 0 |
| 2. | Front left wheel on obstacle (wh1) | -6.5 | -3.03 | -5.85 | -2.79 |
| 3. | Both front wheels on obstacle (wh1 & wh4) | -12.57 | 0.07 | -11.68 | -1.2e-3 |
| 4. | Front right wheel on obstacle (wh4) | -6.69 | 3.17 | -5.85 | 2.79 |
| 5. | Left all wheels on obstacle (wh1, wh2 & wh3) | -0.37 | -9.38 | 4.8e-3 | -9.01 |

To keep safety margin due to both sensor inaccuracy & model inaccuracy, path planning was done with roll, pitch threshold limit of 15°.

For path planning, rover roll & pitch angle is a cost function for path generation to ensure rover doesn't topple while traversing uneven terrain [5].

## III. DETERMINATION OF CRATER DEPTH FROM ROVER ATTITUDE

Post roll down from lander ramp on 23 Aug 2023, Pragyan was parked near the edge of the lander ramp as shown in Fig 3 with heading angle ensuring maximum power generation from solar panel. The next mobility was carried out on 24th Aug on availability of IDSN (Indian Deep Space Network) antenna.

Each mobility of Pragyan was given a unique ID. In this particular section, MID2 is elaborated, in which Pragyan crossed a crater of unknown depth. Using the inverse kinematic model, an estimate of the crater depth is attempted.

The sequence of operations carried out for Pragyan path planning is as follows. A pair of images is taken by left & right camera mounted in front (navcams), as shown in Fig. 4. Using these stereo images, SAC team, generates the DEM (digital elevation map) which is the input to path planning. As shown in Fig 5 the generated DEM is V shaped which is narrow near the rover base and expands as we move away. Due to the close proximity of the crater to rover base it is in the blind zone of the nav cam. In other words it means the crater presence is not captured by navcam and as a result the generated DEM has no information about the crater depth.

The Rover Path Planning software computes the blind zone as the region where DEM width is less than rover's width and the rover is driven in straight line until the last pair of wheels crosses the blind zone [5].

Based on image taken by lander imager, as shown in Fig. 6, it was decided to go ahead with straight path as the crater was perceived to be shallow. It is to be noted that due to the movement of the sun, on the day of MID2 mobility, the crater visibility is better compared to that on 23rd Aug (fig 3). The rover was commanded to move straight and the resulting wheel trace are as shown in Fig. 6. As seen in the figure, rover right side wheels (wheels 4,5 & 6) have crossed the crater.

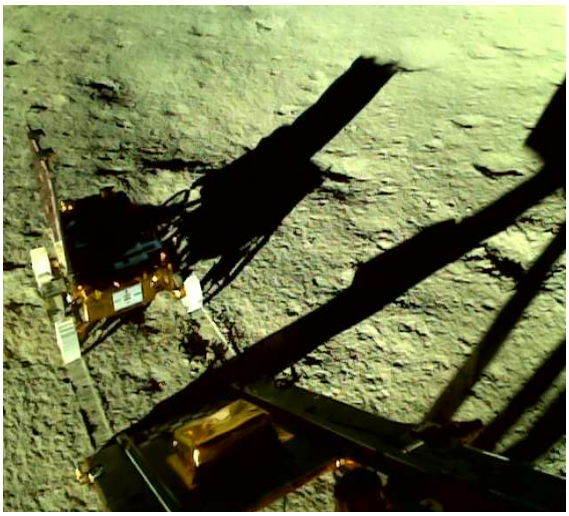

Fig. 3. Pragyan position post ramp down as taken by lander imager on 23.08.23

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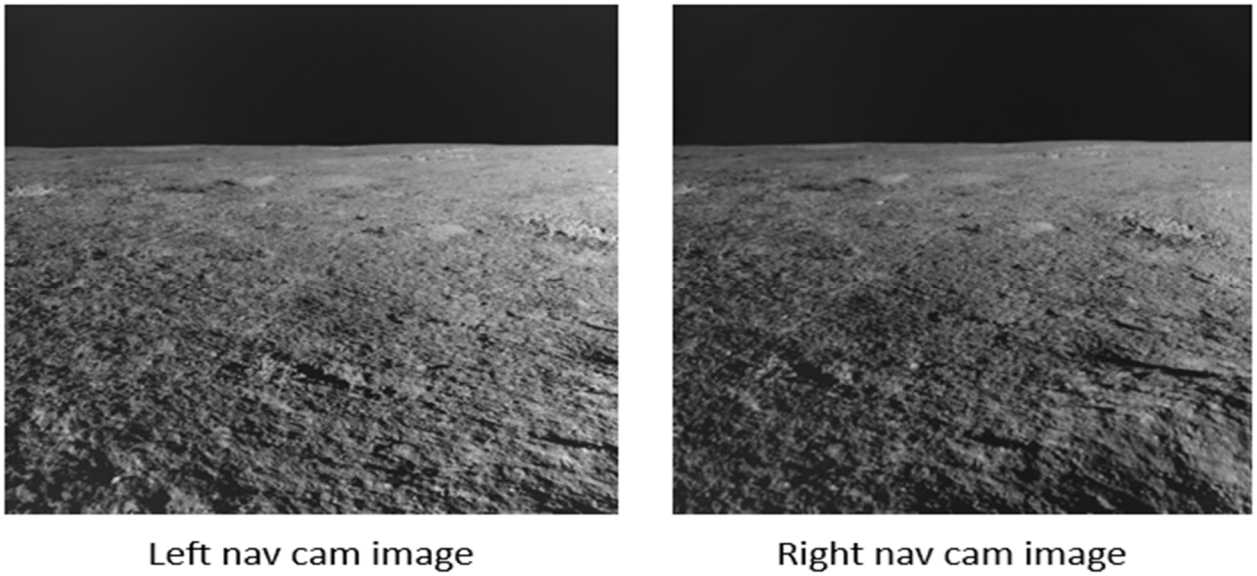


Fig. 4. Pragyan nav cam image on 24.08.23 without crater presence

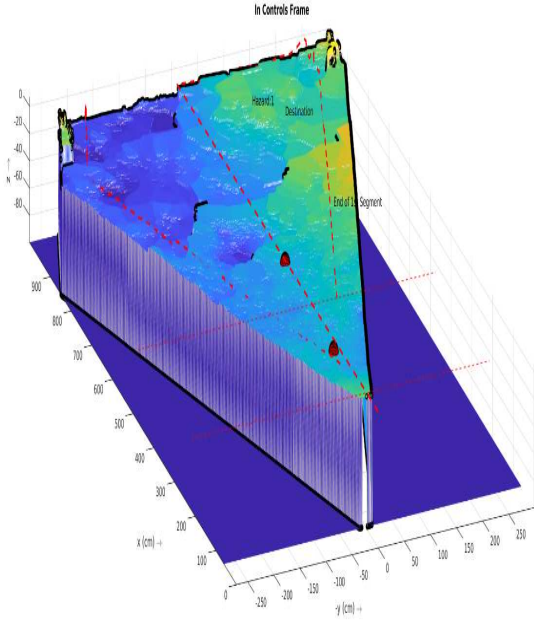


Fig. 5. MID 2 - DEM (digital elevation map) generated from left & right nav cam images

The corresponding rover attitude as sensed by inclinometer is shown in Fig. 7 & Fig. 8. All three right side wheel crosses the crater in segment 1. Each path is divided into segments & the first segment corresponds to mobility over blind zone.

Based on the rover frame, as shown in Fig. 1, rover nose down corresponds to positive pitch and right hand side down corresponds to positive roll. Referring to Fig. 7 & 8 respectively, the pitch is 4.4° & roll is 2.183° when the front wheel is in the ditch. This correspond to rover posture as shown in Fig 9.

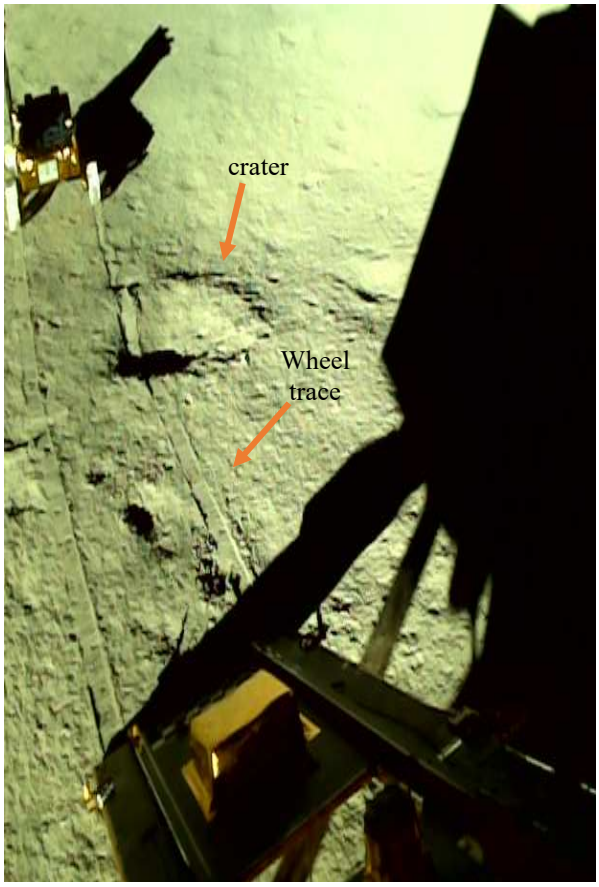


Fig. 6. Rover wheel trace & crater as captured by lander imager on 24.08.23 for MID2

As per inverse kinematic model, assuming remaining five wheels are on flat terrain, for roll & pitch angle to corresponds to above mentioned values, the depth of the crater should be 7.3 cm. This corresponds to $\Theta_4 = 34.625°$ & $\Theta_5 = 26.2948°$. Since rover left hand wheels is on flat terrain, $\Theta_1 = \Theta_2 = 26.29°$. Hence, this particular example shows the application of the geometric model to determine depth of crater one wheel is in, for a given rover attitude with the assumptions of remaining wheels on flat terrain.

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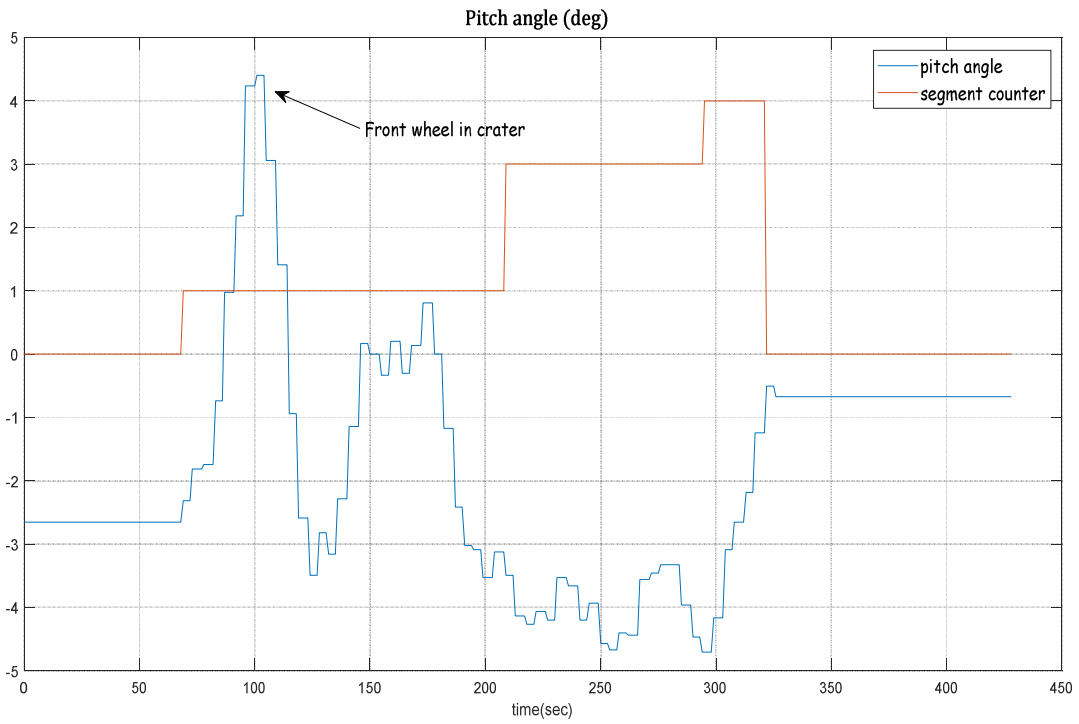


Fig. 7. Pitch angle variation for MID2

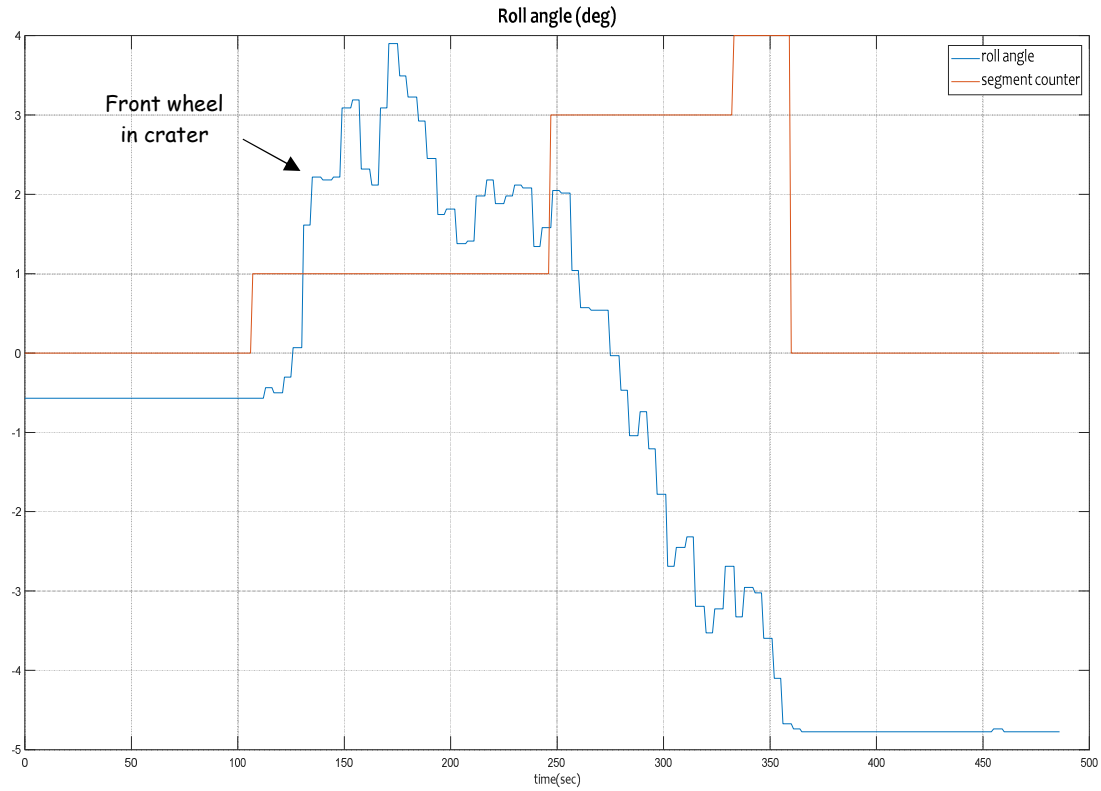


Fig. 8. Roll angle variation for MID2

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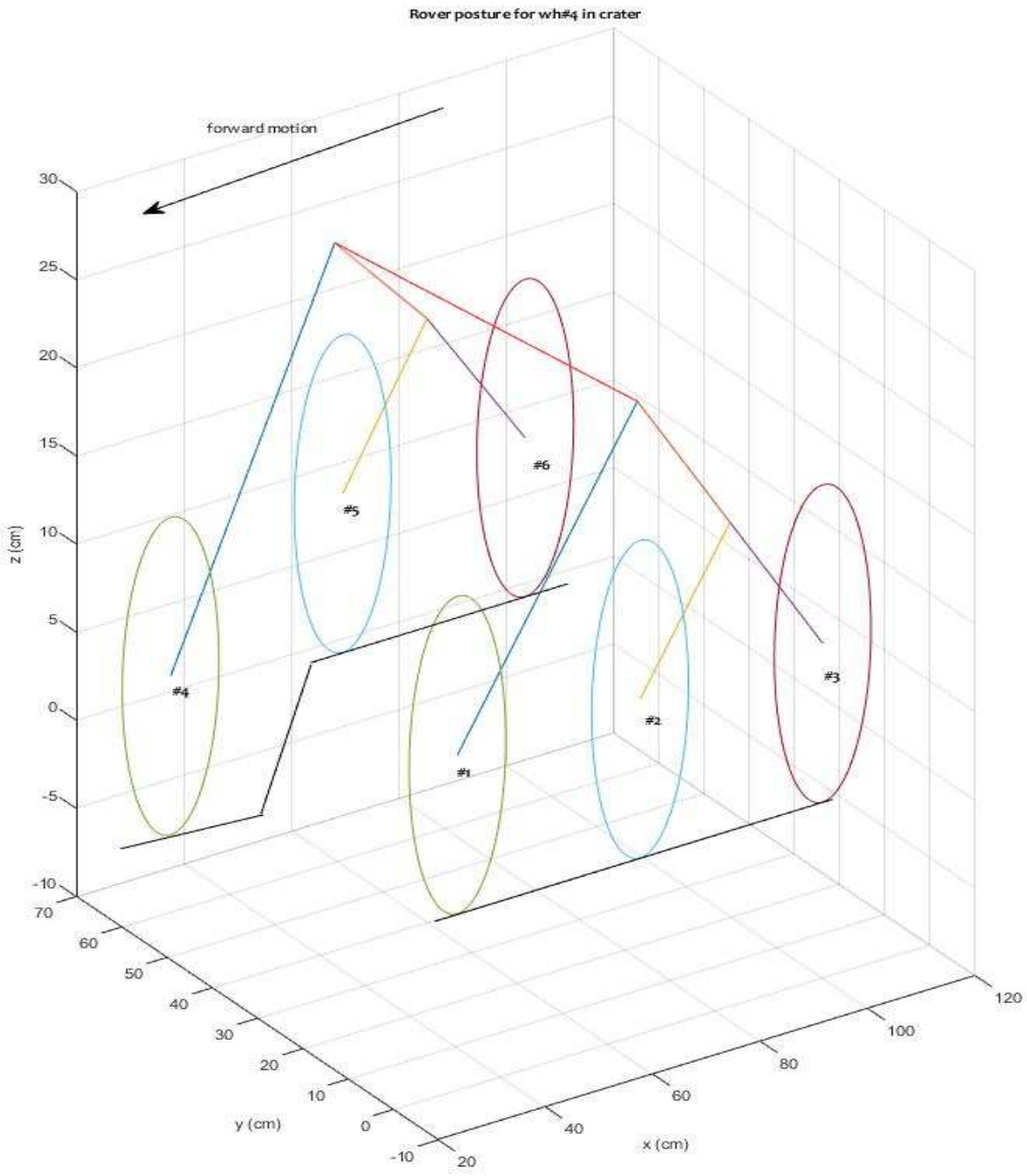


Fig. 9. Rover posture for front left wheel (wh#4) in crater

## IV. Determining Obstacle Climbing Capability

Another application of the kinematic model is to compute the maximum rock height climbing capability while ensuring the rover dose not topple or get damaged due to the obstacle scrapping the under belly or bogie suspension. Based on the terrain information near the landing site or area of science interest, this model can be used to arrive at the desired rover dimension to ensure that the rover has the capability to safely traverse over the terrain.

### *A. Maximum obstacle climbing capability*

The maximum capability is determined ensuring rover safety. The obstacle height should be less than bogie joint height by some margin to avoid damage while climbing rocks. For Pragyan, on flat terrain bogie joint is at a height of 17.3986 cm & rocker joint is at a height of 25.8 cm. The rocker & bogie joint are shown in Fig. 10 for rover wheel #5 placed on an obstacle of height 8 cm. As seen in the figure, wheel #5 is touching the link joining rocker to wh#4. This may result in structural damage or the front wheel losing contact as it gets pushed up due to wheel#5 interference. Hence to ensure safety of Pragyan it was decided to limit the maximum permissible height of obstacle to be 5 cm.

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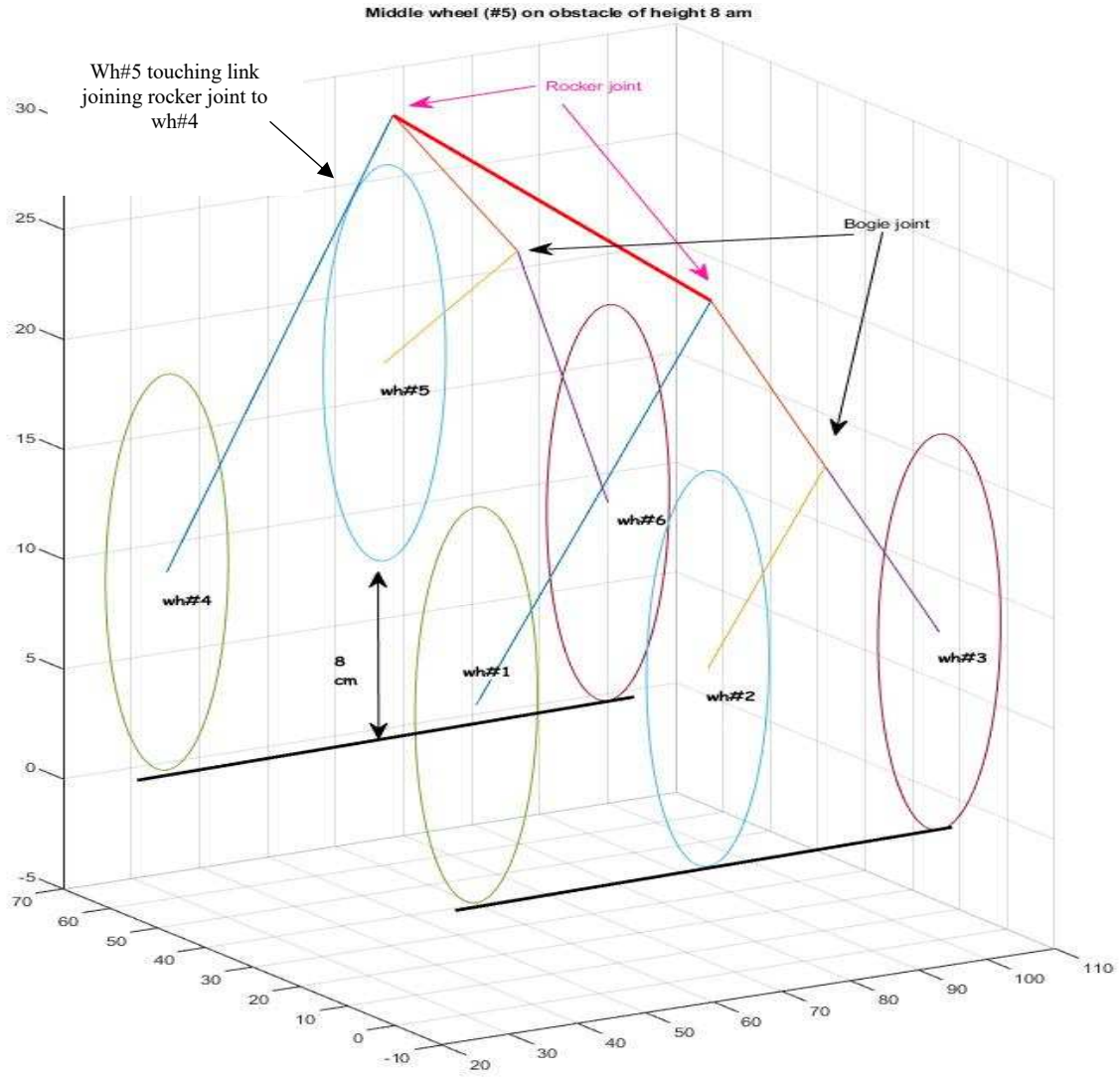


Fig. 10. Rover posture for middle left wheel (wh#5) on obstacle of height 8 cm

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## REFERENCES

[1] Rima Ghosh, Bharat Kumar G.V.P., and Ravi Kumar L, P. Natarajan, K Parameswaran, P. J Bhat, “Inverse Kinematic Analysis of a 4 wheel Rover motion on uneven terrain”, National Conference on Space Transportation System, VSSC, 2011

[2] Chottiner, J.E., "Simulation of a Six- wheeled Martian Rover called Rocker-Bogie", M.S Thesis, The Ohio State University, Ohio, 1992.

[3] K. Iagnemma and S. Dubowski, "Vehicle-ground contact angle estimation with application to mobile robot traction", Proc. 7th Int. Conf. on Advances on Robot Kinematics, Ark ’00, pp. 137-146, 2000.

[4] Hacot, H., "The Kinematic Analysis and Motion Control of a Planetary Rover", Master's Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, May, 1998.

[5] Rima Ghosh et al, “Path Planning for the Pragyaan Rover: Experiences and Challenges,” Proc. 1st International Conference on Space Robotics, pp. 70-75, 2024.

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